Part I

The Strategic Nature of the Tactical Satellite

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CADRE/AR
Director, Airpower Research Institute
401 Chennault Circle
Maxwell AFB AL 36112-6428

Title of Paper: The Strategic Nature of the Tactical Satellite

Author: Edward B. Tomme, D. Phil., Lt Col, USAF (ret)
edward.tomme@schriever.af.mil
Department of Physics, United States Air Force Academy
Air Force Space Battlelab, Air Force Space Command

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Executive Summary

> *Tactical: dealing with smaller engagements, smaller in scope, effect, and duration.*
>
> —Department of Defense Dictionary of Military and Associated Terms

The concept of operationally responsive launch to get tactically useful payloads into orbit quickly and cheaply has been around for many years.[1] Operationally responsive launch has yet to be realized, but is likely getting much closer to reality. Air Force Chief of Staff General John Jumper alluded to the need for ORS when he said, "Small satellites will have a play once we get past the paradigm of space launch being an episodic event."[2] There is a definite need for a capability to place inexpensive payloads into space on a very short time schedule.

Developing *tactically* useful payloads that can take advantage of responsive launch, however, is a different matter. A combination of *physical constraints* placed on satellites by orbital mechanics and *operational requirements* placed on their payloads by the missions that can be performed from space prevent all but the most rudimentary tactical missions from being attainable for the foreseeable future. Foreseeable tactical satellite capabilities mean that tactical requirements of persistence and coverage can only be filled by constellations of relatively large numbers of satellites. If these missions are carried out, they will cost hundreds of thousands to millions of dollars per hour in overhead, costs that would seem to be beyond the reach of tactical or even theater commanders.

Using General Jumper's metric of "effects on the ground," the difficulties in tactical satellites actually being tactical become apparent.[3] Continued funding of the tactical satellite program under the misguided notion that they can provide tactical effects on the ground only serves to drain scarce budgetary resources from other programs that could provide these desired effects. The myth of the tactical satellite is that they are tactical.

No mission exists where a tactical satellite could provide primarily tactical effects.[4] In a computer programming language, "tactical" would be a reserved word. When one uses it to sell a program to a warrior, the warrior has a very specific understanding of what that technical term means: applying to small-scale, short-lived events, usually involving troops in contact.

Orbital assets can and do perform a huge number of operationally relevant missions. In this case, however, they appear to be a round peg in a square hole—a solution being forced into a mission where there are much better answers. In all likelihood, tactical satellite advocates do not intentionally misrepresent the tactical nature of their product. The misuse of the very specific term "tactical" appears to come from ignorance, not malice. However, before any additional funding is expended toward this concept, realistically achievable effects of tactical satellites should be carefully evaluated against the requirements of tactical warfighters. Warriors of the next few decades should not die needlessly because programs that actually had a chance of providing needed tactical effects were not available because the money that would have funded them went to the mythical tactical satellite.

Accordingly, this paper will present the tactical satellite program in the best light possible to show that even if all systems work better than advertised, the projected tactical satellite program still fails to provide required tactical effects on the ground. These generous programmatic assumptions will demonstrate that the failure to provide effects is not due to engineering shortfalls, where more money might solve the problem, but instead is due to physical limitations that cannot be overcome until the satellites become inexpensive enough to field constellations of hundreds simultaneously.

As an example of how limited the effects from a tactical satellite can be, a 5-ball satellite constellation optimized to cover Baghdad from an altitude of 500 km can only deliver, on average, about five minutes of communications coverage every half-hour or a single two-minute imagery pass every hour. It should be obvious to any tactical warfighter that such levels of coverage are inadequate for their needs. A tactical warfighter

needs persistent imagery and constant communications. Getting a snapshot or minutes of communications every hour or so is not very useful at the tactical level, where the time scale of the action is measured in minutes or seconds.

To get around the marginally useful coverage times provided from LEO, tactical satellite proponents propose using a highly elliptical "Magic Orbit" to give near-continuous coverage.[5] When at the useful part of its orbit, a satellite in a magic orbit is about 8000 km above the earth, over 16 times further than a likely 500 km circular tactical satellite orbit. At this distance, conventional imagery missions are ineffective due to resolution limitations.

At the current time one of the biggest limitations on tactical use of satellite communications is that the soldier must stop his vehicle and point a high-gain antenna toward the stationary satellite to get reception. The reason for this limitation is that communications satellites are very far away and the signals they emit are relatively weak. The signal from a satellite in a magic orbit would be about 20 times stronger, but instead of coming from a stationary communications satellite it now comes from a moving one. The soldier's problem is now compounded—he has to stop and acquire a satellite in a constantly changing location, adding one further complication to a problem he doesn't need in the middle of a battle.

Finally, the space environment in which a satellite in a magic orbit must operate is extremely hostile. According to three tactical satellite proponents, "It is not surprising that no traditional systems have ever flown in this regime: the radiation environment is extremely severe."[6] Traditional systems, ones that do not rely on small boosters, ones that use space-hardened electronics and shielding, ones that are not limited to a few hundred pounds of mass, avoid the magic region. It seems improbable that small satellites built on a shoestring would be able to do better.

Even if tactical satellites in LEO could provide tactically useful effects on the ground, a dubious assumption at best, they would end up costing tens of thousands to millions of dollars per hour overhead. The ability to launch small payloads into orbit on an operationally responsive timescale, however, does have its

utility. The effects that such an ability could deliver, however, are almost exclusively strategic, and the strategic effects could be extremely useful.

The purpose of this paper is as much to educate the tactical satellite proponent on what the warfighter needs as it is to educate the warrior on what tactical satellites can offer. The tactical satellite program needs a change of name and a change of focus as the effects it can provide lie much closer to the strategic end of the spectrum of conflict. Such a change of focus would allow operationally responsive launch to compete in the *strategic* arena where it actually has a great deal of utility. As it stands, the money the program receives comes from money intended to support tactical warfighters on the ground, support it cannot provide.

Ed "*Mel*" Tomme

List of Assumptions

The following assumptions will be used in this paper to ensure that the results are biased in favor of the tactical satellite program. Cost and performance numbers used are the most optimistic available from briefings and writings of tactical satellite proponents. Other assumptions all overstate the actual capabilities of any possible tactical satellite.

For the purposes of this study, it will be assumed that:

- the science and engineering portion of the tactical satellite program will work perfectly
- perfect environmental conditions will exist (24 hours of daylight per day and perpetually cloudless skies) so the onboard sensors will always be able to perform their missions
- the program will meet all of the goals of being able to launch the advertised payload mass at will to the advertised altitude (any combination of mass and altitude that equates to the energy in 1000 lbs. at 100 NM) for the advertised cost ($20M) and keep it there for the advertised lifetime (1 yr)
- financial estimates will only use acquisition costs for the booster and satellite; the considerable infrastructure, operations, and exploitation costs will not be considered
- all quoted orbits will be optimized to maximize the amount of time over a specific tactical region, an optimization that will give the absolute best cases for the time and cost analyses of a satellite destined for control by a theater commander
- satellite FORs will be better than commonly attained by commercial and military assets already on orbit (horizon for SIGINT, five degrees above the horizon for comm/BFT, and 45 degrees off nadir for imagery)
- no sensor FOV limitations will be applied; every sensor can fully and continuously utilize the much larger satellite FOR

- energy models used to calculate the decrease in mass that the same booster could boost to a higher altitude will not include the mass of the stage required for orbital insertion
- calculations to determine the required number of satellites in a constellation to provide persistent coverage will use less stringent long-term averages instead of the worst-case scenarios that would actually need to be employed.

Taken together, these assumptions greatly overstate the capabilities of tactical satellites. It is extremely unlikely that any actual implementation of real tactical satellites will approach this assumed performance. Even with the following analysis based on such overtly optimistic assumptions, this study will clearly demonstrate the inability of tactical satellites to provide effects that are of use to a tactical warrior.

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Section 1

Introduction

This paper is divided into several sections. As stated in the Executive Summary, physical limitations on satellite orbits and physical limitations on satellite sensors will play a large role in this analysis of the tactical effectiveness of tactical satellites. A fairly substantial amount of space will be devoted to showing how optimal orbits can be achieved, both for the circular and elliptical orbital regimes proposed by tactical satellite proponents. This paper will also examine how the fields of regard for various spacecraft sensors further limit the effectiveness of satellite contributions. This discussion will be somewhat technical, but is required to understand the full story behind the promise of tactical satellites. Finally, these physical satellite limitations will be discussed in the context of limitations to tactical effectiveness as judged by potential contributions to warfighters on the ground.

As mentioned above, tactical satellites require a combination of successful engineering and practical operational utility to prove themselves worthy of further funding. The engineering part of the problem is currently being worked by hundreds if not thousands of people from such organizations as the AFRL, the AFSPC's SMC, and other organizations including the Navy and Army. There are at least six TacSat demonstrations in various stages of funding, planning, and construction.[7] These demonstrations appear to be precursors to a more generalized tactical satellite program with the goal of producing and storing a number of these operationally responsive satellites and boosters sufficient to allow on-demand launch of customized satellites in response to a COCOM's contingency needs.[8]

Whether the technology to accomplish the ACTD goals or even to accomplish the longer-term goals for the envisioned generalized tactical satellite program exists is not the purpose of

this paper. The validity of those science projects will soon be demonstrated and nothing written here will have any effect on their success or failure. Instead, to best demonstrate the effects of physical constraints and operational requirements on the ability of tactical satellites to perform a tactical mission, this paper will assume that the science and engineering portion of the tactical satellite program will work perfectly and will achieve all of the goals of being able to launch the advertised payload mass at will to the advertised altitude for the advertised cost and keep it there for the advertised lifetime. The numbers for calculating these favorable conditions come from briefings presented by tactical satellite advocates. Perfect environmental conditions will also be assumed so the onboard sensors will always be able to perform their SIGINT, imagery, comm, and BFT missions regardless of weather or day/night conditions. By postulating the existence of a perfectly working technological product, we can then concentrate on evaluating the operational utility part of the problem.

What is meant by a "perfectly working technological product" is a point worthy of discussion. From various briefings and published articles attributed to tactical satellite proponents, the goals of the generalized tactical satellite program appear to be to launch the energy equivalent of a 1000 lbs. payload into a 100 NM (185 km) circular orbit and keep it there for between six months and a year for an acquisition cost of about $20 million per satellite and booster combined.[9] Again, these are the baseline goals for a generalized tactical satellite program; the mission goals of the various TacSat ACTDs are somewhat different.

As will be explained in more detail in the body of this paper, physics requires all satellites to move. Except for special cases well outside the parameters associated with tactical satellites, it is not possible to "park" a satellite over a spot on the ground to get persistent coverage. As will also be explained later, the FOR available to a satellite, the area on the ground that its sensors can see, depends on the mission and performance of the sensor. The combination of satellite motion and FOR combine to limit the useful amount of time a satellite is overhead.

The results presented below will thus assume the use of an optimized orbit designed to give the maximum time for the

satellite overhead, or contact time. Contact time is the most important parameter for tactical warfighters, as it is the only time that the expensive satellite effects will be available to them. By optimizing the contact time, we also maximize the average number of satellite passes per day, maximize pass duration, minimize the amount of time the satellite is not overhead (gap time), and minimize the cost per hour overhead.

Orbits optimized for maximum contact time are not necessarily the ones that are used operationally, as those orbits may be (correctly) optimized for different operational constraints such as a constant solar illumination angle. However, orbits optimized to maximize contact time give the absolute best cases for time and cost; all other orbits will necessarily give less time and will cost more per hour overhead. To provide a simplified baseline for the remainder of the paper, satellite capabilities over the specific target of Baghdad associated with two representative LEO orbits will be discussed up front. Tables 1 and 2 below summarize the optimized number of satellite passes, pass durations, and gap times for two circular orbit altitudes. The parameters used to generate these results define the tactical satellite program as that term is used in this paper.[10]

The 100 NM orbital altitude is shown as it is the reference altitude for a generalized tactical satellite program.[11] (The way the altitude is frequently quoted in tactical satellite literature, 100 NM, is equal to 185 km. All other distances in this paper will be quoted in kilometers.) At that altitude, atmospheric drag would bring down a satellite without propulsion capability in a matter of days,[12] so it is obviously a non-player for an actual tactical satellite. This represents the approximate energy available from the two responsive launch boosters potentially available in the near-term for tactical satellite launches, DARPA's FALCON and SpaceX's Falcon 1.[13] Energy is a complicated function of altitude and payload mass. Generally you have to trade one of these parameters to get better performance from the other. Since the 100 NM orbit is too low for real tactical satellites, we have to give up some of the 1000 lb. payload mass to allow the orbit to move higher where drag will not be as significant a factor. Mass tradeoffs will be discussed in more depth later in this paper. The 500 km orbital altitude is shown as it is about as high as any funded TacSat ACTD is designed to orbit.[14]

Data for single satellites as well as for a 5-ball constellation are shown. The single satellite data are useful to determine baseline information. The 5-ball constellation information is shown since many briefings on tactical satellites use a variation of this implementation to increase coverage time.[15] By increasing the number of satellites, the number of passes is multiplied and the average gap between passes is essentially divided by the number of satellites in the constellation. The average pass duration and cost are unchanged since they depend on each satellite individually.[16] Note that the goal acquisition price per satellite and booster is now more than $20 million each and they are designed to last between six months and one year to keep the construction costs down by using COTS electronics.[17] Again, numbers that will lead to a predetermined solution that will not support tactical satellites have not been assumed. These numbers are those espoused by tactical satellite proponents. The definition of what a tactical satellite is comes from published numbers in the responsive space community.

Table 1. Contact time and cost data for a 100 NM circular orbit over Baghdad.[18]

Mission	100 NM (185 km) Circular Orbit				
	Average number of passes per day	Average pass duration	Average gap between passes	Average Percent Useful Time Overhead (Duty Cycle)	Cost Per Hour Overhead
	SINGLE SATELLITE				
SIGINT	8.3	4 min 29 sec	2 hr 48 min	2.7 percent	$88K
Comm/BFT	7.0	3 min 8 sec	3 hr 22 min	1.6 percent	$150K
Imagery	3.0	33 sec	8 hr 01 min	0.1 percent	$2M
	5-BALL CONSTELLATION				
SIGINT	41.8	4 min 29 sec	34 min	13.2 percent	$88K
Comm/BFT	34.9	3 min 8 sec	40 min	7.8 percent	$150K
Imagery	14.9	33 sec	1 hr 36 min	0.6 percent	$2M

Table 2. Contact time and cost data for a 500 km circular orbit over Baghdad.

Mission	500 km Circular Orbit				
	Average number of passes per day	Average pass duration	Average gap between passes	Average Percent Useful Time Overhead (Duty Cycle)	Cost Per Hour Overhead
	SINGLE SATELLITE				
SIGINT	9.7	7 min 47 sec	2 hr 20 min	5.6 percent	$43K
Comm/BFT	8.7	6 min 12 sec	2 hr 39 min	3.9 percent	$61K
Imagery	4.6	1 min 40 sec	5 hr 10 min	0.5 percent	$429K
	5-BALL CONSTELLATION				
SIGINT	48.6	7 min 47 sec	28 min	27.8 percent	$43K
Comm/BFT	43.5	6 min 12 sec	32 min	19.4 percent	$61K
Imagery	23.0	1 min 40 sec	1 hr 02 min	2.7 percent	$429K

As can be seen from the tables, SIGINT and comm/BFT missions get significantly better performance than imagery missions. This difference is due to the severely constrained FORs available to imagery missions. As an example, a 5-ball SIGINT mission optimized to provide coverage over Baghdad at the tactical satellite reference altitude of 100 NM would provide about 4½ minutes of coverage out of every 38 minutes and would cost $88 thousand an hour overhead. A similarly optimized imagery mission would only provide about 30 seconds of coverage every hour and a half at a cost of at least $2 million per hour. Even when control of the satellite payload is actually delegated to tactical level, as is envisioned using the Air Force Space Battlelab's extremely innovative VMOC program,[19] the ability to be able to acquire and image more than one or two specific targets in the short time the satellite is overhead is technically ambitious. Thus, depending on one's priority for imagery, it could be many hours or days before the desired image is taken.

While boosting the satellite altitude to a more realistic 500 km increases contact time, it simultaneously degrades image resolution by a factor of almost three and signal strength for all missions (imagery, comm/BFT, and SIGINT) by a factor of over seven.[20] Overcoming these mission degradations involves adding larger sensors and associated equipment, increasing weight and making it that much more difficult to get the payload to the higher orbit.

Tactical SIGINT is equally problematic from tactical satellites. The signals can only be collected at best for seven minutes each half hour, giving spotty information about a dynamic battlefield. BFT and comm missions are similarly ineffective from LEO circular orbits. It is almost inconceivable to contemplate sending a commander into combat after telling him that he'd only be able to communicate across distances of more than about 10 km for 3 to 6 minutes out of every 30 or 40, the coverage time he would get with the sparse networks advertised by tactical satellite proponents. A large network similar to the 66 satellites in the Iridium constellation can provide good coverage,[21] but even at a relatively inexpensive $20 million per satellite the expense of such a network would put it out of reach of the tactical commander.

The following few sections of this paper will discuss in detail the limitations that physics puts on tactical satellites, first dealing with orbital mechanics and then with sensor performance, both in LEO and in magic orbits. The discussion will be somewhat technical but not to a level that is beyond an educated layman. There are a large number of claims made in this paper; these technical sections are where the proof of these claims is located. Should the reader's interest lie elsewhere, these sections can be skimmed. A less technical discussion of the conclusions reached from these data begins in the section entitled The Operational Utility of Optimized Tactical Satellites.

Section 2

Physical Constraints on Orbiting Objects

We will first look at some of the physical constraints imposed by the stated tactical satellite orbital parameters and will then attempt to optimize them to show how they could deliver improved performance. In order to understand these physical constraints we need to gain a rudimentary understanding of what makes satellites move.[22] Orbital mechanics is a topic that, while not difficult to understand, is not commonly understood by warriors. A basic concept that appears to be commonly misunderstood is that satellites cannot hover above a target, providing stay-and-stare persistence. All satellites must move to stay in orbit. If we drop a *stationary* satellite it will fall toward the center of the earth, *perpendicular* to the earth's surface, regardless of whether we drop it from two meters or from orbital altitudes. The only way a satellite can stay in orbit is for it to have some motion *parallel* to the earth's surface that keeps it from crashing into the planet since it is continually falling due to the part of its motion that is perpendicular to the surface. It can also be shown that the closer a satellite is to the earth, the faster it has to move to prevent such a crash. For most satellites very close to the earth in LEO, they must move so quickly that it takes them only about 90 minutes to circumnavigate the earth.[23]

It has been shown that all satellites must move in order to stay in orbit. That statement seems to contradict what many warriors believe they understand: there are some satellites that do not move. When they stop in the middle of a battle to set up a SATCOM link, they point to a specific spot in the sky and are certain to get a connection with a stationary satellite. In reality, these "stationary" satellites are moving, but they're moving at such a rate that it takes about 24 hours for them to go around the earth and the earth moves at the same rate beneath them. They only appear to be stationary to an earthbound observer. To an

observer anywhere else, it is apparent that, like the earth itself, they really do move. Such satellites are in geostationary orbits, a special case of GEO. GEO satellites can only be placed in orbits 35,800 km above the earth, a huge distance equal to almost six times the earth's radius of 6,400 km. It takes a very large booster, lots of energy, and a great deal of money to put a payload into GEO. Additionally, sensors must be considerably larger, more sensitive, and more robust at GEO altitudes in order to sense the same parameters as sensors on a LEO satellite.

Another concept that is not commonly understood relates to the direction a satellite's motion has to take. All closed orbits are circles or ellipses, figures that can be drawn on a sheet of paper or any other plane. While most people understand that fact, a further constraint is that the plane of the orbit must also contain the center of the earth. This limitation means that satellites can only appear stationary if they are in geosynchronous equatorial orbits (the plane containing the equator also contains the center of the earth—Figure 1 illustrates this concept). A GEO satellite placed over the equator would thus appear to be stationary (a geostationary orbit), while a GEO satellite whose orbital plane is tilted with respect to the equatorial plane by an angle known as its orbital inclination would continue to take 24 hours to orbit but would cycle the latitude it is directly over between the northern and southern latitudes equal to its inclination once every day. Figure 2 depicts the concept of orbital inclination. Note that the inclined orbital plane also contains the center of the earth.

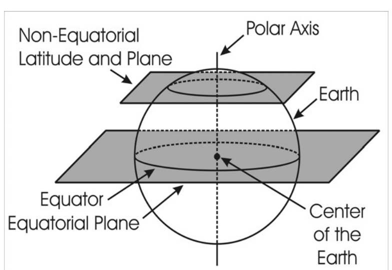


Figure 1. The equatorial plane contains the center of the earth and can thus host an orbit. The plane containing any other line of latitude does not pass through the center of the earth and thus cannot support an orbit.

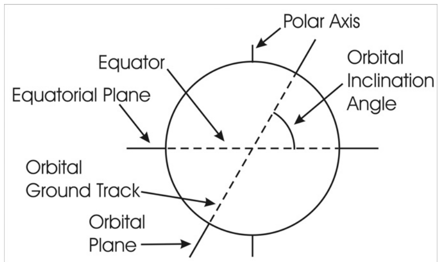


Figure 2. Depiction of the orbital inclination angle.

For the present, only satellite orbits that are circular will be discussed. Later we will examine what effect trying to put a satellite into an elliptical orbit will have on its tactical utility. The combination of a satellite's altitude and inclination are the two attributes that allow us to calculate how often a satellite will be over a specific target location. One final piece of information is needed, however, to allow us to know how much of its time overhead will actually be useful to us. That information is known as the satellite's FOR, sometimes referred to as its footprint. The FOR is the area on the ground that can be used for the mission the satellite is required to perform.[24] It should be apparent that FORs get bigger the higher the satellite orbits; think of how much further you can see from the top of a building than you can see from ground level.

Fields of regard are mission driven. For example, the ground-based node of a ground-to-space comm/BFT link generally requires the space-based link to be a specified angle above the horizon, generally five to ten degrees, to ensure connectivity.[25] The field of regard for such a mission would be the area on the ground from where the satellite would be at or above the specified angle above the horizon. In contrast, a signals intelligence mission detecting radio transmissions only needs to have line of sight to the emitter it is trying to detect, so its field of regard extends to the horizon as seen from the satellite.[26]

Imagery satellites have much more restrictive FORs. In order to properly analyze overhead images, the images cannot be taken from too shallow an angle. If they are, foreshortening makes it very difficult to determine where objects are with respect to each other. It is also much more difficult to interpret what the images represent when the viewing angles are shallow; try to read this page from a point of view near the edge of the sheet and you'll

see why: the letters become so foreshortened as to become unreadable. Atmospheric effects are much more pronounced when the image is taken at a shallow angle due to the much greater distance through the atmosphere the light has to travel from the object. Finally, the resolution of an image, the ability to distinguish small, closely-spaced objects from each other, is directly related to how far away the object is.[27] The shallower the angle, the further away the objects being imaged and the poorer the resolution. At shallower than certain angles, the images become useless as the information desired (discriminating between tank and truck, for example) can no longer be obtained. For these and other reasons, imagery satellites seldom look more than about 30 degrees off-nadir, where nadir is the direction of an imaginary line extending from the satellite straight down toward the center of the earth.[28]

It must be noted that whether the requirement is ground-based (i.e., five degrees above the horizon) or satellite-based (i.e., 45 degrees off-nadir), the FOR describes a specific circle on the ground. For any given altitude, any satellite-based FOR can be converted into a ground based angle and vice versa. Numerous figures will be shown later in this paper with data for multiple mission types on the same plot. Remembering that the angle label is just one of convenience based on the mission may simplify interpretation of these plots. As an example of this concept, Figure 3 and Figure 4 show the relative sizes of these mission-driven fields of regard for a satellite orbiting at 100 NM and 500 km, respectively. Other satellites in LEO would have FORs with similar radius ratios, but the entire group would be proportionately larger or smaller on the map depending on whether the orbit was higher or lower than those depicted. The first part of this paper will only consider the most favorable FOR, where the satellite can see all the way to the horizon. This approach will allow us to concentrate on the problem of orbital optimization with fewer distractions. Once that optimization problem is understood, the FORs will be restricted to examine their effects on target coverage by satellites.

It is also very important to realize that just because a target is in the FOR of the satellite, it is not necessarily being imaged by the payload. Satellites typically do not image their entire FOR during a single pass. Especially for the high resolution imagery

necessary for the tactical warfighter, only a tiny fraction of the whole FOR can be seen by the camera's FOV at any one time. As part of the goal to discuss tactical satellites in the most favorable terms, the limitations of the sensor FOV have not been included in this study, but keep in mind that those limitations will severely limit the optimistic numbers presented in this paper.

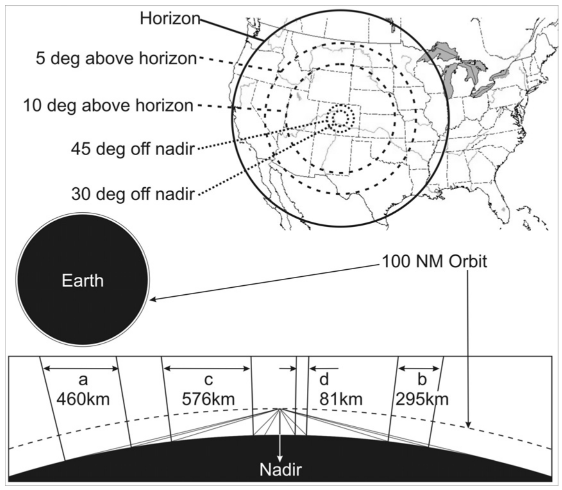


Figure 3. Fields of regard from 100 NM (185 km). In the upper portion of the figure, the dotted lines represent imagery-related fields of regard, the dashed lines represent comm/bft-related fields of regard, and the solid line represents the sigint-related field of regard. The middle left portion shows the earth and a 100 NM orbit to scale. The lower portion shows an enlarged side view of the fields of regard for the 100 NM orbit. The distance labeled "a" is the difference between the radius of the horizon field of regard and the 5 deg above horizon field of regard; b: between 5 and 10 degrees above the horizon fields of regard; c: between 10 degrees above horizon and 45 degrees off-nadir fields of regard; d: between 45 and 30 degrees off-nadir fields of regard.

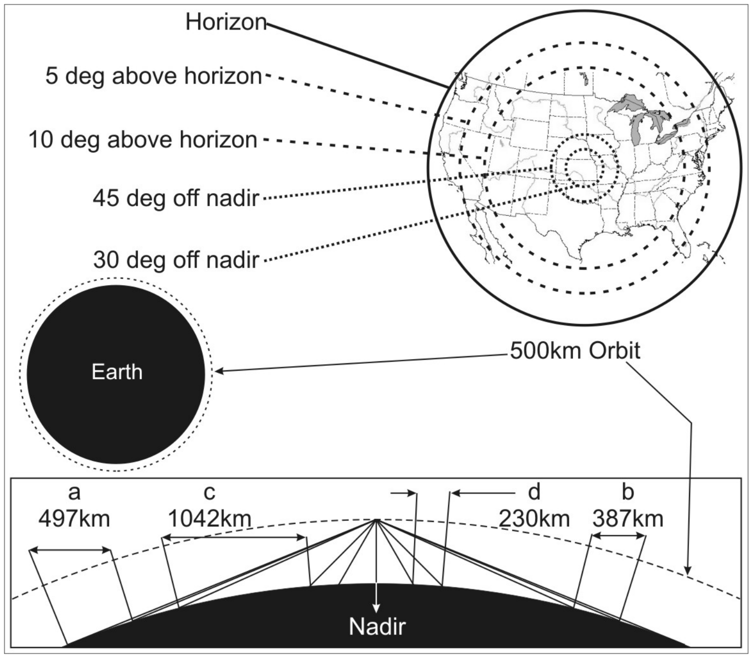


Figure 4. Fields of regard from 500 km. In the upper portion of the figure, the dotted lines represent imagery-related fields of regard, the dashed lines represent comm/BFT-related fields of regard, and the solid line represents the SIGINT-related field of regard. The middle left portion shows the earth and a 500 km orbit to scale. The lower portion shows an enlarged side view of the fields of regard for the 500 km orbit. The distance labeled "a" is the difference between the radius of the horizon field of regard and the 5 deg above horizon field of regard; b: between 5 and 10 degrees above the horizon fields of regard; c: between 10 degrees above horizon and 45 degrees off-nadir fields of regard; d: between 45 and 30 degrees off-nadir fields of regard.

Orbit Optimization to Maximize Contact Time

We're now to the point where we can start putting some of this seemingly esoteric knowledge about satellite orbits to good, practical use. The goal is to determine how to optimize a satellite orbit for a tactical application. Some time will be spent discussing orbital optimization as it is a key part of argument presented. In addition to assuming perfect programmatics for the discussion of tactical satellites, these hypothetical, perfectly operating satellites will be placed in orbits that give them the absolute best chance for success. "Optimization" would seem to imply that we would like just as much time overhead, or contact time, from the satellite as possible. "Tactical" tells us that we are interested in optimizing the orbit for a specific location, perhaps a city or a very small region of a country but most definitely not for continental or global coverage. Again, to give tactical satellites the maximum benefit of the doubt, the best-case scenario of a horizon FOR will be discussed. The absolute maximum contact times possible will be calculated using this largest-possible FOR. Remember, however, that FORs are mission-dependent, and most missions will not be able to take full advantage of a satellite's LOS to the horizon.

Ignoring sensor performance, we have four parameters at our disposal that actually make a difference: orbital altitude, orbital inclination, satellite FOR, and target location. If we plot the contact time a satellite would achieve from the combinations of these parameters we should be able to discern some trends on how to optimize our tactical orbit. For a generalized tactical optimization study, we are not interested in the exact day-to-day times that a particular satellite will be overhead. Instead, our true interest lies in the long-term average contact time with the satellite. Long-term averages also simplify our target location parameter as well, as the symmetry of the sphere of the earth means that we really only need to specify the latitude of the target; all longitudes crossing the specified latitude will have the same long-term average contact times.[29] Symmetry also implies that northern and southern latitudes will have the same long-term average contact times.

The accompanying charts (Figures 5 to 7) plot the average daily contact time a single satellite with a horizon FOR would have over three cities at different latitudes: Bogotá, Colombia (4 degrees north latitude); Baghdad, Iraq (33 degrees north latitude); and Oslo, Norway (60 degrees north latitude).[30] Discussions of constellations of satellites will come later. These cities were chosen to give representative samples of low, mid, and high latitude results. Since two of the four free parameters (target latitude and FOR) are specified in this example, the plots should compare the other two for completeness. Thus, the horizontal axis of our plots varies satellite altitude while the vertical varies satellite inclination. Altitudes are varied between 150 and 600 km; the lower limit being where the atmosphere becomes thick enough to bring a satellite down in a matter of several days and the upper limit being somewhat arbitrary but around the published value for the funded TacSat programs and substantially higher than the general tactical satellite altitude reference orbit of 100 NM (185 km). Inclinations are varied between zero degrees (equatorial orbits) and 105 degrees. The three plots are somewhat similar in shape, varying only in detail. They are approximately symmetrical about the horizontal 90 degree inclination line.[31]

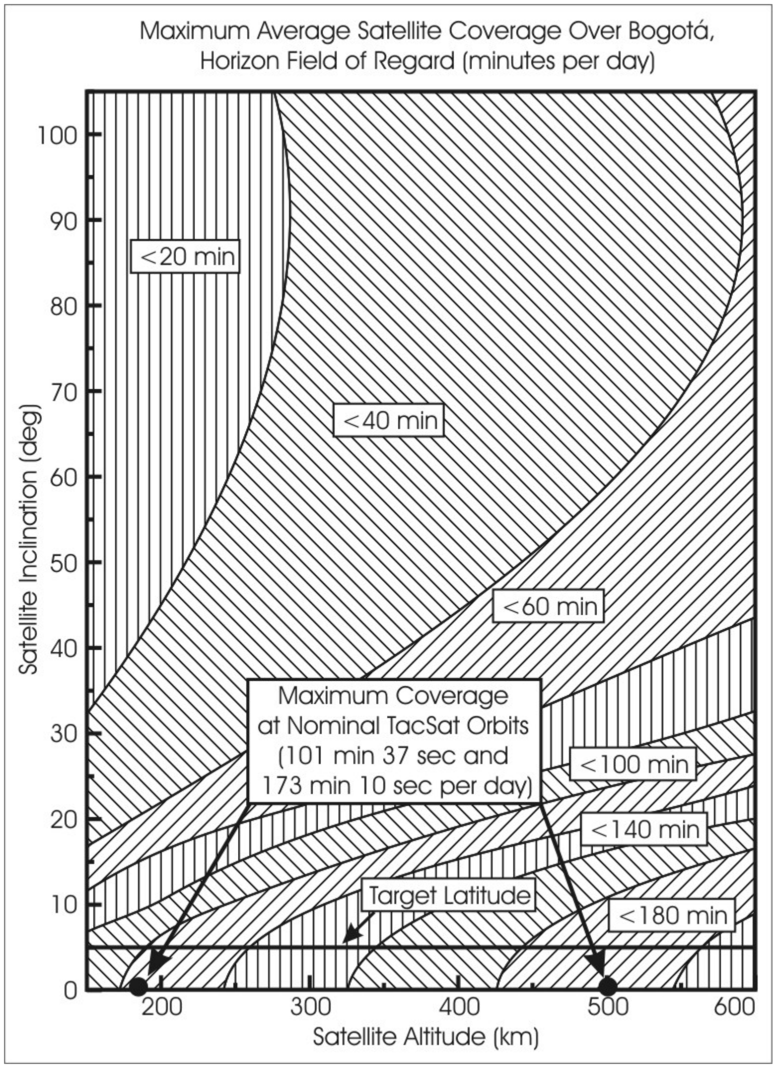


Figure 5. Long-term average contact times over Bogotá with a horizon FOR.

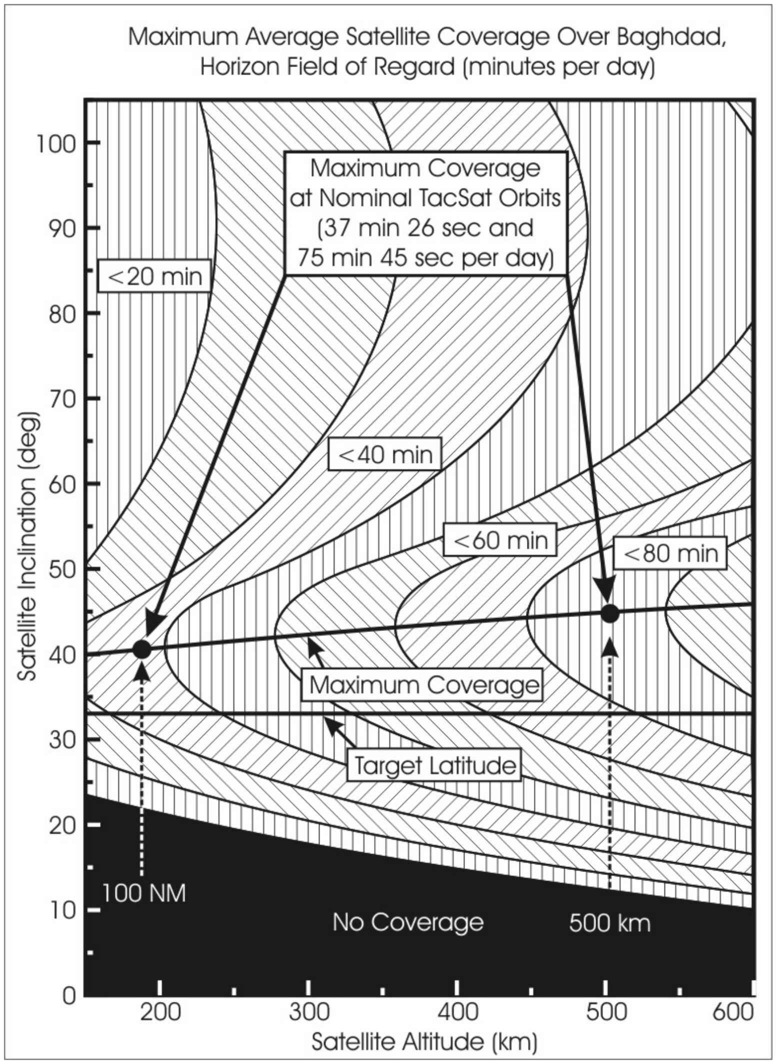


Figure 6. Long-term average contact times over Baghdad with a horizon FOR.

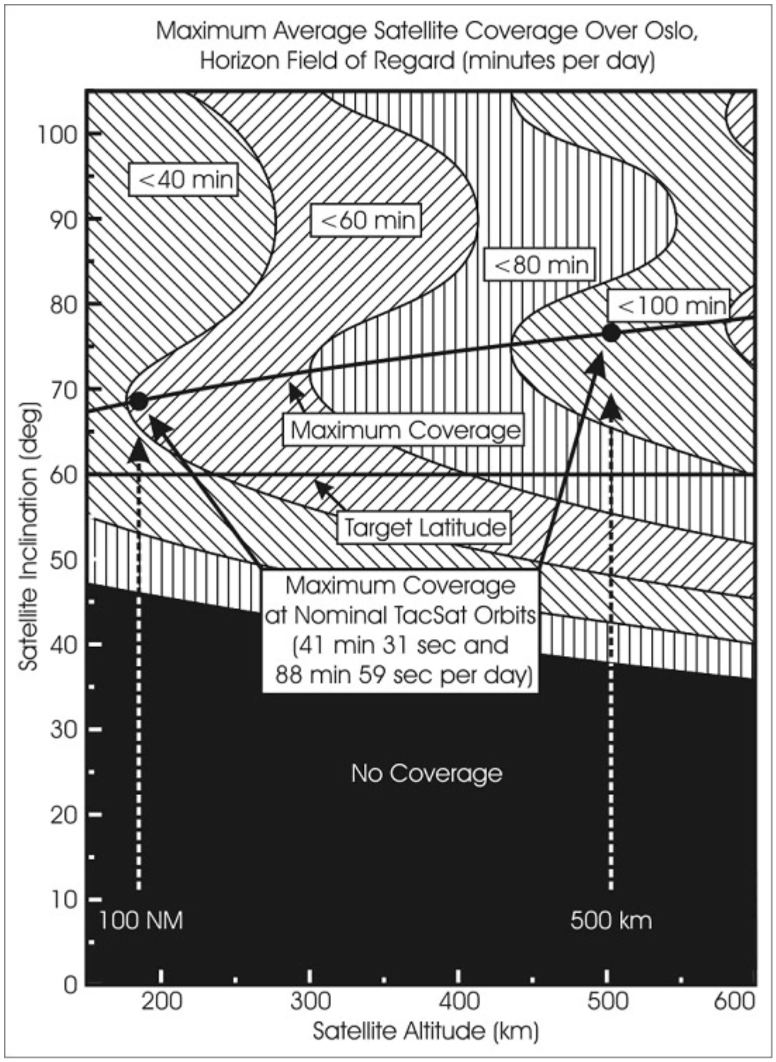


Figure 7. Long-term average contact times over Oslo with a horizon FOR.

There are black areas at the bottoms of the two higher-latitude plots (Baghdad and Oslo) showing the combination of inclinations and altitudes that provide no coverage of the targets in question. From Figure 2 it should make sense that a satellite with a shallow inclination angle and low altitude might never be able to see a target located at a high latitude. To give a more explicit example, Figure 8 shows a satellite ground trace for an orbital inclination of 15 degrees. The swaths centered along the ground trace show the approximate size for horizon FORs for several satellite altitudes. Note that all of the swaths cover Bogotá while none would ever allow Oslo to be imaged. The higher altitude (larger) swath would allow Baghdad to be imaged. These examples illustrate why the Oslo plot (Figure 7) has the largest black area, and also illustrates why the black areas become narrower at higher altitudes.

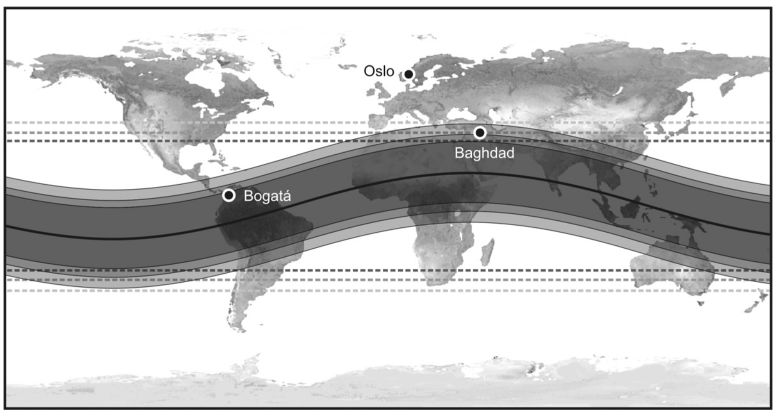


Figure 8. Satellite ground trace showing horizon FORs for a 15 degree inclination orbit from 100 NM (185 km; inner, darkest shaded region), 300 km (middle shaded region), and 500 km (outer, lightest shaded region). All points between the dotted lines corresponding to the peaks and troughs of the shaded regions would eventually be covered by the satellite.

From the plots it will become obvious that there is a certain orbital inclination that, for any given altitude, maximizes the contact time. As an example, let us say we are trying to

maximize the contact time over Baghdad at the tactical satellite reference altitude of 100 NM (185 km). We find 185 km along the bottom of Figure 6 and begin to move upward from zero inclination orbits to higher inclination orbits, noting the contact times as we go along. At first, we cross the black zone that indicates that a satellite at those low inclinations will never pass over Baghdad.

Eventually we come to the point at about 22 degrees inclination where the satellite FOR begins to pass over its target city. The contact time is short, less than 20 minutes per day in the region where the hatchings are vertical, but soon become longer and wider as we move further up the chart and wider portions of the FOR begin to pass over the city. These longer contact times are indicated by the first diagonal hatched region where they are between 20 and 30 minutes per day, and then between 30 and 40 minutes per day in the second diagonally-hatched region.

If we continue further upward, the contact times begin to drop off again to below 30 then below 20 minutes per day. Obviously, we passed through the point at which the contact time was maximized for our choice of altitude and target. That point is indicated on the plot at about 41 degrees inclination, where the absolute maximum contact time for these conditions is about 37 minutes per day. The line of maximized contact time for any orbital altitude is shown on the chart for easy reference.

For the Bogotá plot the inclination that maximizes contact time is equatorial; for Oslo the approximate inclination is 68 degrees. Coincidentally, those inclinations are quite close to the cities' latitudes.[32] We have discovered our first truism for tactical satellites: to optimize contact time the inclination of the orbit should be very close to the latitude of the target. Also notice the unstated corollary: no satellite can be optimized for more than one target latitude.[33] The horizon FOR for these plots is the largest available to a satellite. It will be shown later that the smaller the FOR, the closer the optimal inclination is to the target's latitude and the more critical the optimal orbital inclination becomes to maximizing contact time.

Now that we have examined the effects of changing the satellite's inclination on contact times by moving vertically on the charts, let us look at what varying the altitude (moving

horizontally) will do. Our second truism is immediately apparent from the plots: increasing the orbital altitude increases the contact time.[34] This result is due to two causes. As discussed earlier, you can see farther when you get higher.[35] Increasing your altitude physically increases the size of the FOR, which in turn has a positive effect on contact time. Additionally, moving to a higher orbit slows the satellite down a bit, more closely matching its speed with that of the earth's rotation. The FOR thus moves more slowly across a target, also tending to increase the contact time.

Finally, the point of view of the plots will be changed a bit to demonstrate a third truism: targets near the equator and the poles receive better optimized coverage than mid-latitude targets. In fact, the optimized contact time is almost symmetrical about a target latitude of 45 degrees. With a bit of thought you can prove this truism to yourself. It is possible to put a satellite in orbit directly over the equator, since the plane of the equator contains the center of the earth. If your target is on the equator, the satellite will pass over it every time it goes around the earth. If your target is at mid-latitudes, even an optimized orbit will not necessarily pass over it every single time around the earth; depending upon the match between the satellite's and the earth's rotational speeds, sometimes the satellite will reach its maximum inclination over the target, at other times it will reach its maximum latitude some distance away from the target (see Figure 8 for an example). If your target is at one of the poles, you can put your satellite into a polar orbit with an inclination of 90 degrees. No matter what longitude along which the satellite makes its approach, it will still pass directly over the pole on every orbit.

The layout of these plots must be changed to demonstrate this truism. Instead of showing satellite *altitude* on the horizontal axis, Figures 9 and 10 show target *latitude*. Instead of a *fixed target location* as was used before, the *altitude is fixed* from plot to plot. The lower right corner of the plot is now the region where the satellite's inclination is too low to allow its FOR to pass over the high-latitude targets. The broad band running from the lower left to the upper right is the band of optimized inclinations. A dark line indicating the exact location of the optimized inclination for each target latitude runs through the

middle of that band. Note that it generally follows the inclination-equal-to-latitude truism discussed above. Once the inclination gets too high with respect to the latitude, coverage drops off as can be seen in the upper left portion of the plot. Finally, the very high coverage numbers—up to two hours per day of contact time for the tactical satellite reference altitude—for optimized orbits near the equator and the poles are clearly visible. Also as discussed above, it is apparent from comparing the two figures that moving higher does improve contact time: moving from 185 km (100 NM) to 500 km gives about a factor of two increase in contact time across the board. As tactical warfighters we generally do not get to choose the latitude of our targets to a great extent. Thus this truism dealing with target location is less applicable to us than the other two, but it is nevertheless an important fact.

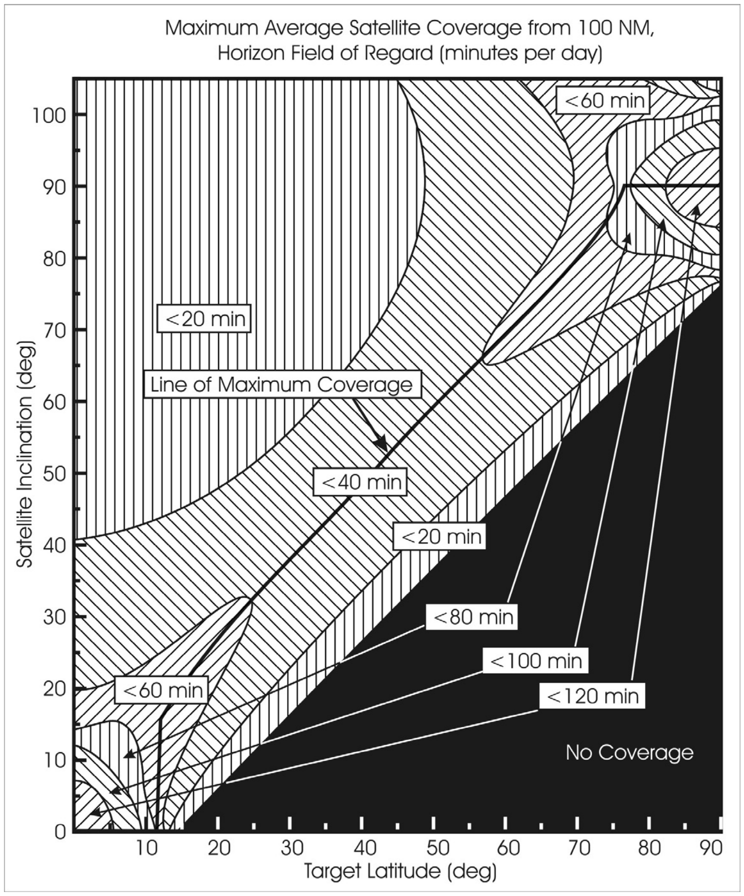


Figure 9. Horizon FOR satellite coverage from 100 NM (185km).

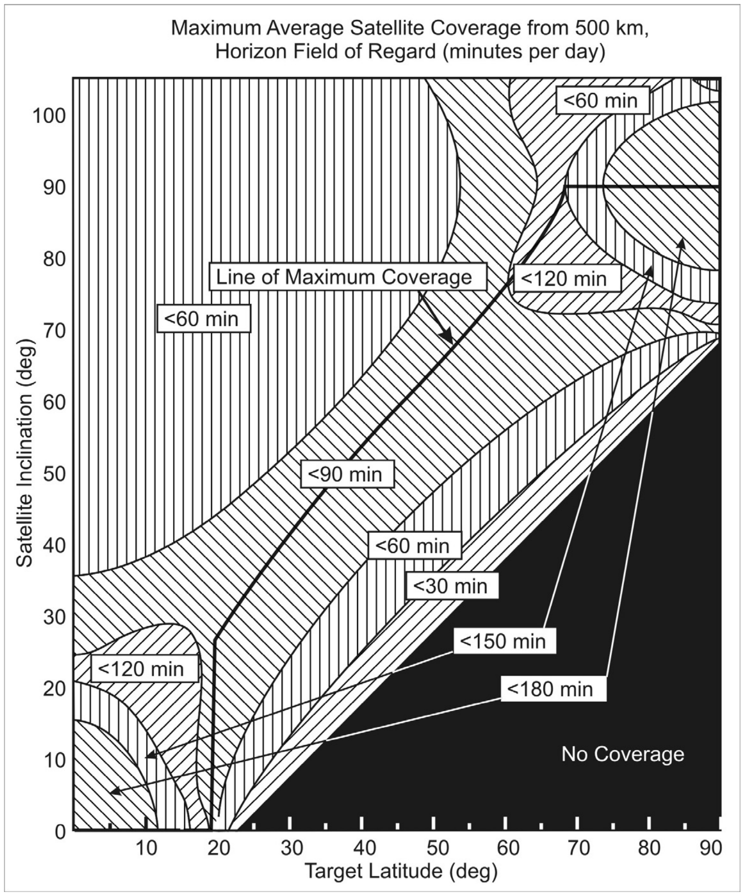


Figure 10. Horizon FOR satellite coverage from 500 km.

We now have a good idea of how to optimize a satellite's orbit to obtain the maximum contact time over a specified target: put it as high as possible and match its inclination to the desired target's latitude. For the remainder of this study, the use of optimized orbits will be assumed. This assumption will further ensure that we examine the operational utility of the tactical satellite concept in the best possible light: a platform that perfectly meets program goals and has been launched into an orbit that gives it the best chance for tactical success.

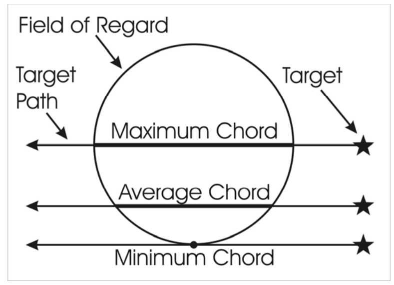
Average Daily Contact Times, Pass Durations, and Coverage Gaps

Figures 5 to 7 (pp. 15-17) display the long-term average contact time per day for the specified combinations of inclination, altitude, target location, and FOR. For the general tactical satellite reference of a 100 NM orbit, the plots clearly show that the maximum contact time per day one could expect to achieve would be approximately 100 minutes for Bogotá, 37 minutes for Baghdad, and 42 minutes for Oslo. For the 500 km orbit, the maximum times at these locations would be approximately 170, 76, and 90 minutes. What the plots do not clearly show is how many passes per day, how long each pass would be, and how much of a gap in coverage exists between passes. It is fairly easy to calculate the exact contact times for a real-world satellite using any of a number of commercially-available software packages. Although we cannot get the *specific* time-of-day contact time information that we could for a real-world satellite, it is reasonably straightforward to calculate similar *average* information from the long-term average contact time plots.

A contact occurs when the FOR of a satellite passes over the target. As the FORs on the earth's surface are circles centered on the satellite's nadir point, different contacts will not have the same durations. Their durations depend on the distance of the closest approach of the satellite's nadir point to the target. Figure 11 illustrates this concept. If we assume the FOR passes over the target in a straight line,[36] the minimum pass duration would be an almost instantaneous flicker should the target pass at the very

edge of the FOR. The pass duration increases to its maximum value when the satellite passes directly over the target, dragging the entire diameter of its FOR across the target.

Figure 11. Three different target paths through a FOR give three different transit lengths (pass durations).



For the present study of long-term averages, the average duration of a contact will be related to the average chord length of a circle of diameter equal to the FOR.[37] The maximum chord length is the FOR diameter. The average and maximum chord lengths are obviously dependent upon orbital altitude. Using the relationship that distance equals velocity times time, the average and maximum pass durations can then be found by dividing these chord lengths by the ground speed of the satellite, which is also altitude dependent. Figure 12 displays the average pass durations for the range of satellite altitudes used in the long-term average contact time plots shown previously.[38] (This figure and many of the subsequent figures will show a number of different FORs. However, for the present topic of orbital constraints, only the best-case horizon FOR will be discussed. These figures will be revisited later when we begin to discuss sensor limitations and their relationship to FORs.)As an example, for the orbital altitude of 500 km the average and maximum contact times per pass are 7 min 47 sec and 12 min 13 sec for a horizon FOR, respectively. The maximum contact time will almost never be attained, but it is presented here to demonstrate the absolute best-case scenario. Likewise, it is equally unlikely to have the target pass through the minimum chord.

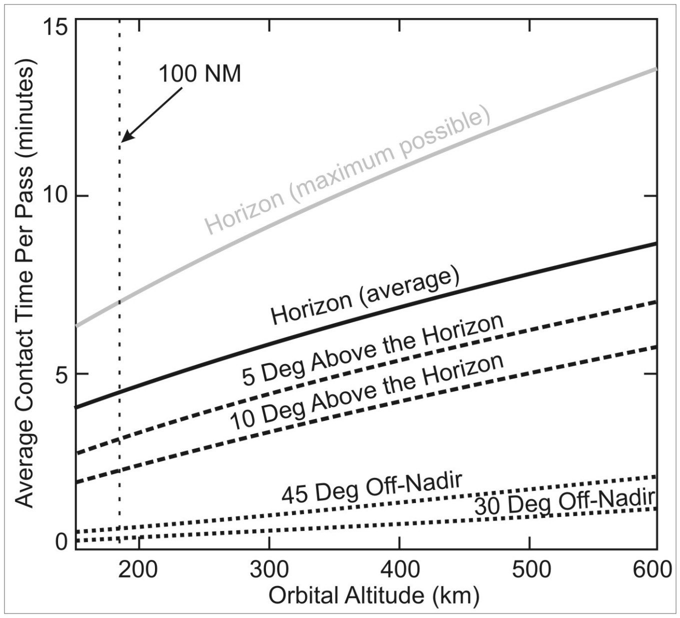


Figure 12. Average pass durations per satellite pass. FORs for three different mission types are shown: SIGINT (horizon), comm/BFT (5 and 10 degrees above the horizon), and imagery (45 and 30 degrees off-nadir). The grey, upper line labeled horizon shows the maximum possible contact time for comparison with the average horizon contact line below. All other maximum lines would similarly be about 1.5 times higher than the average lines shown.

In contrast to Figure 12, which shows *individual* pass durations, Figure 13 shows the optimized contact time *per day*. It is essentially a plot of the heavy line passing approximately diagonally through Figure 9. By dividing the optimized average daily contact time from this figure by the average pass durations from Figure 12, we can determine the average number of contacts (satellite passes) per day.[39] By inverting the number of contacts per day we can also determine the days per contact, or the average revisit time between passes. The gap time, the time when a satellite is not overhead, is just the revisit time minus the pass duration. We can also figure the cost per hour overhead by

dividing the acquisition cost of $20 million by the amount of time the satellite would be overhead during the upper limit of its advertised lifetime, one year. Again, the cost estimates will be the most favorable possible to the tactical satellite program, as they use the upper end of the six month to one year advertised lifetime and only include booster/satellite acquisition and not infrastructure or operations costs.

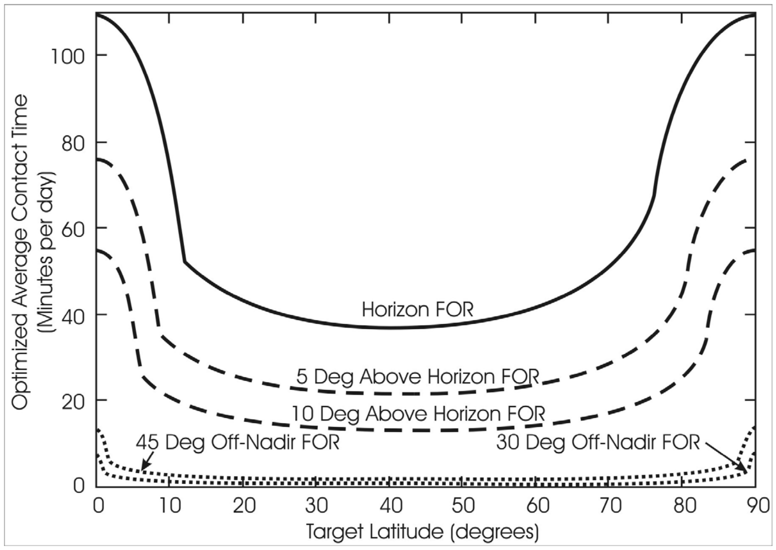


Figure 13. Comparison of satellite coverage for different FORs from an orbital altitude of 100 NM. The solid line represents a SIGINT mission, the dashed lines represent comm/BFT missions, and the dotted lines represent imagery missions.

Figures 14 and 15 show these results for satellite altitudes of 100 NM and 500 km, respectively. Note that at the 100 NM tactical satellite altitude reference with a horizon FOR you could expect a single satellite to pass over Baghdad (33 degrees latitude) about 8 times per day and be in view for 4½ minutes on average (from Figure 12), resulting in an average gap in coverage of almost 3 hours. The cost of this availability (contact time) is about $88,000 per hour.

Placing the satellite higher in a 500 km orbit improves performance a bit. From that vantage the satellite will make ten 8-minute passes per day with an average gap between passes of about 2½ hours. The cost for availability at this higher altitude drops to $43,000 per hour.

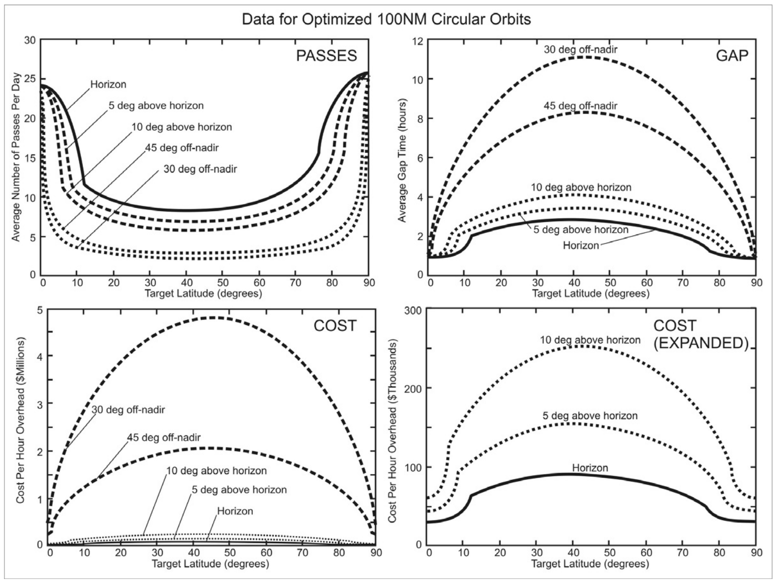


Figure 14. Number of passes, average gap time, and cost data for a tactical satellite in a 100 NM orbit. The curves represent data for three mission types: SIGINT (solid), comm/BFT (dashed), and imagery (dotted). Cost data are shown in two panes as the scales between imagery and the other missions are quite disparate.

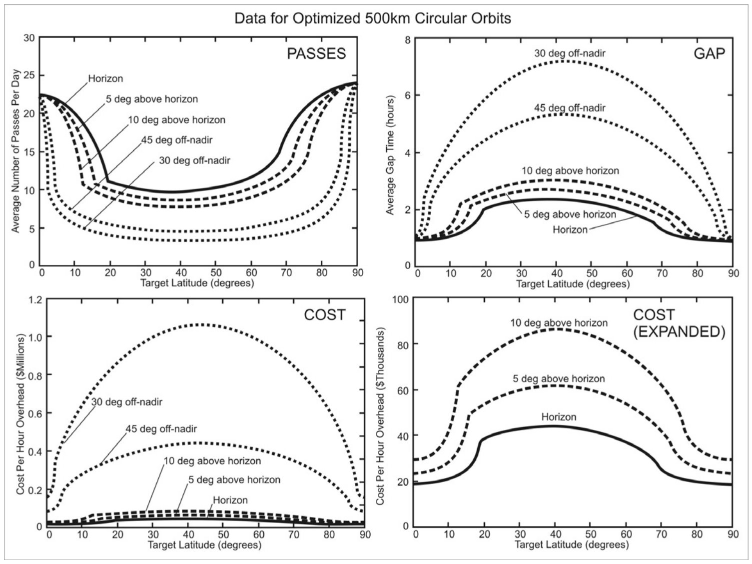


Figure 15. Number of passes, average gap time, and cost data for a tactical satellite in a 500 km orbit. The curves represent data for three mission types: SIGINT (solid), comm/BFT (dashed), and imagery (dotted). Cost data are shown in two panes as the scales between imagery and the other missions are quite disparate.

It is also important to note that commanders have *no* control over exactly when the passes for any satellite would occur. To them, the pass times appear to be pseudorandomly distributed.[40] There would be a number of times where the coverage gaps were much smaller and times where the gaps would be much larger.

Sensor Constraints on Optimized Orbits

The figures calculated above represent the absolute best-case average daily contact times, average pass durations, and average revisit rates that can be obtained, limited only by orbital constraints on the satellite as a whole. To this point in our discussion operational constraints on the satellite payload have not been applied. It is now time to apply those constraints as well.

We have been discussing optimized orbits for horizon FORs. For a few SIGINT missions, these FORs are valid. For other SIGINT missions as well as for the comm, BFT, and imagery missions, they are not. The reason the horizon FOR is not generally valid is due to sensor requirements. For SIGINT, comm, and BFT missions, the emitter of the signal being detected must have an unobstructed LOS to the sensor on the satellite.

Electromagnetic radiation is the basis of virtually all the signals sensed remotely, whether at optical, radio, or other frequencies. Radio waves behave almost identically to light waves, the only differences being due to the different wavelengths of the two forms of electromagnetic radiation. Think of someone shining a laser pointer across a room. If an obstacle gets in the way, the light is blocked. Similarly, if a mountain gets between your car and the broadcast tower of your favorite radio station, the station fades out. Its signal is blocked, too, when LOS is broken.[41]

SIGINT sensors are generally opportunists; they will take in and analyze any signal they can detect. Thus, there is generally no requirement for them to be a certain angle above the horizon. If the terrain is flat and they can see all the way to the horizon, great. If there are mountains in the way, the sensor simply waits until it establishes LOS to the emitter and then begins collecting. For these reasons, it is assumed the horizon FOR is valid for most SIGINT missions.

Comm, BFT, and imagery missions are different. They cannot use the horizon FOR. Comm and BFT missions cannot afford to be opportunistic—the capability has to be there all the time. Comm/BFT providers typically require their platforms to be at least five degrees above the horizon, with ten degrees being more commonplace. While this requirement does not guarantee coverage in the bottom of a deep canyon, it does ensure that the odd tree, house, or hill will not normally interfere with direct LOS to the platform. Restricting the FOR to five degrees above the horizon has a significant effect on the performance delivered by an optimized orbit. Compare Figures 16 and 17, which show the comm/BFT performance over Baghdad, with the horizon FOR performance previously shown in Figure 6 (p. 16). Not only has the "no coverage" region increased in size, the available daily contact time has also dropped across the board.

For example, the maximum contact time per day at the tactical satellite reference altitude decreases by 41 percent from 37 to 22 minutes per day. The physical reason for this drop in performance can be seen in Figure 3 (p. 11).

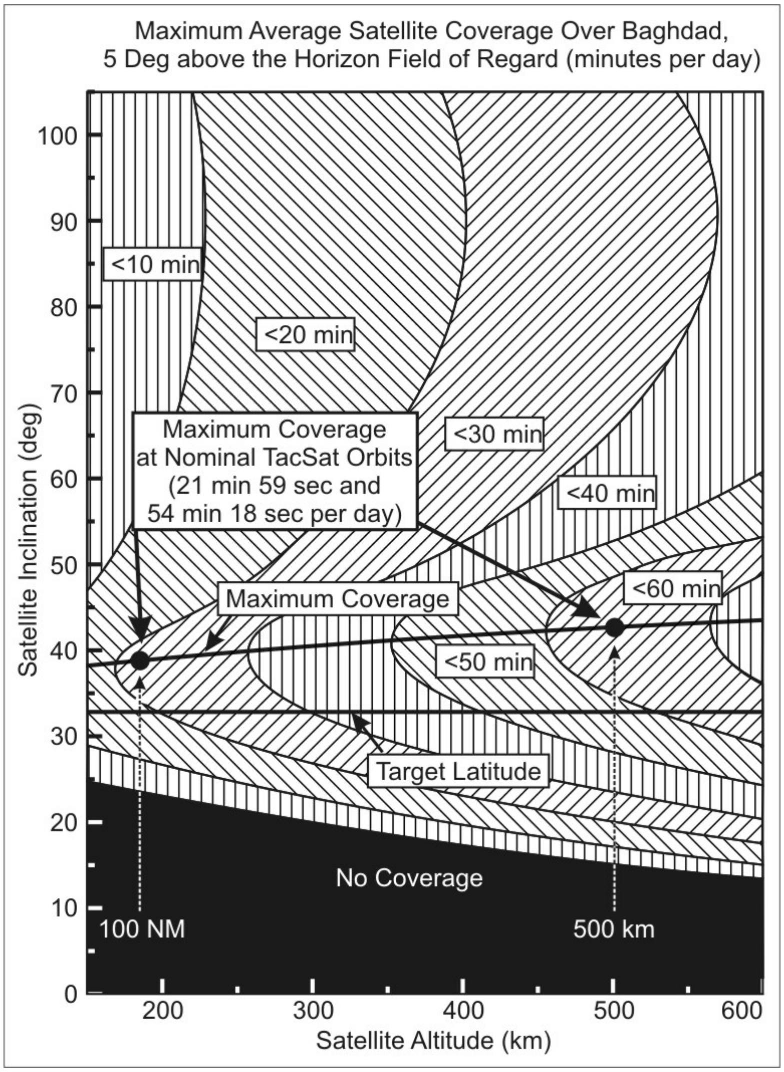


Figure 16. Long-term average contact times over Baghdad with a 5 degree above the horizon FOR.

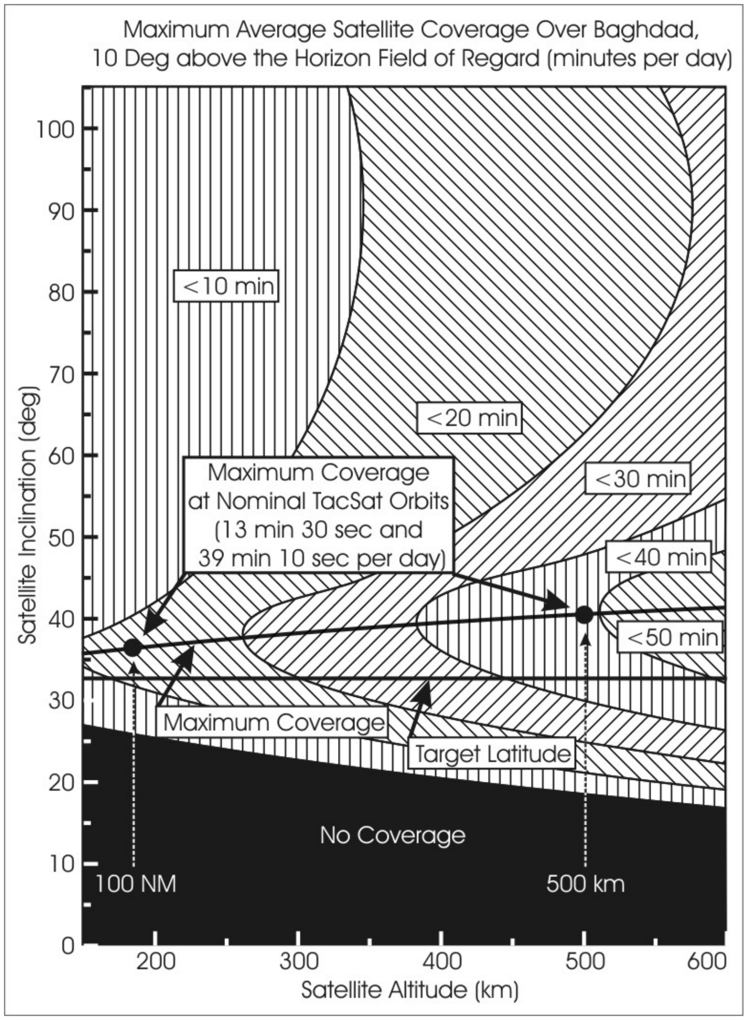


Figure 17. Long-term average contact times over Baghdad with a 10 degree above the horizon FOR.

Imagery sensors are even more tightly constrained. Not only must they have LOS like the other missions but, as discussed previously, they cannot look too far away from the vertical (nadir) without introducing a host of problems. These problems include foreshortening, excessive atmospheric degradation, and decreased resolution that can make analysis exceedingly difficult if not impossible. Additionally, many imagery sensors operate in the visible light region. It is exceedingly difficult for these sensors to function at night. Even night-capable infrared sensors have a hard time penetrating significant cloud cover. This analysis will ignore the non-trivial limitations of weather and darkness and will present optimized numbers that reflect an ability for imagery sensors to operate at full capability 24/7, realizing that this assumption will significantly overstate the actual capability.

Now compare Figures 18 and 19 (for imagery FORs) with the similar figures we just revisited for typical SIGINT and comm/BFT FORs. These figures show data for satellites optimized to cover Baghdad at a range of altitudes but with different FORs. Figure 9 (p. 22), Figure 20, and Figure 21 show similar data for a fixed altitude of 100 NM across the complete range of target latitudes. Notice the significant, across-the-board decrease in coverage time as the FOR is narrowed from horizon to comm/BFT to imagery FORs. Also notice the significant narrowing of the peaks as the FOR is narrowed.

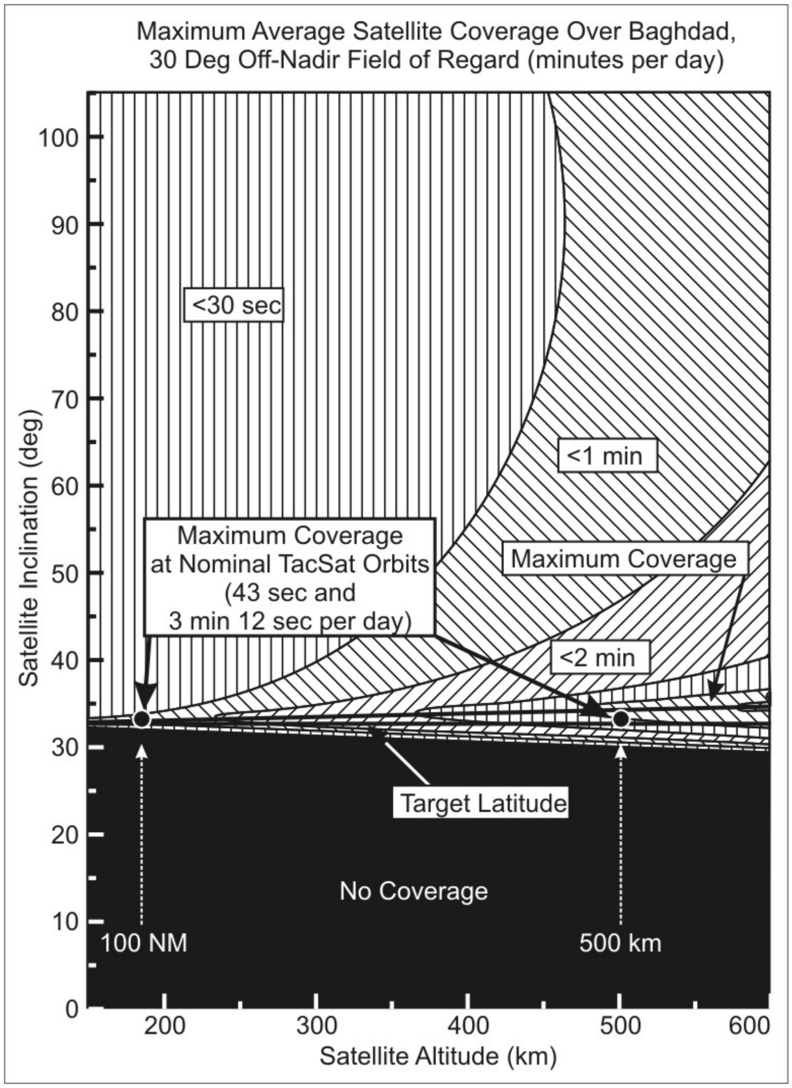


Figure 18. Long-term average contact times over Baghdad with a 30 degree off-nadir FOR.

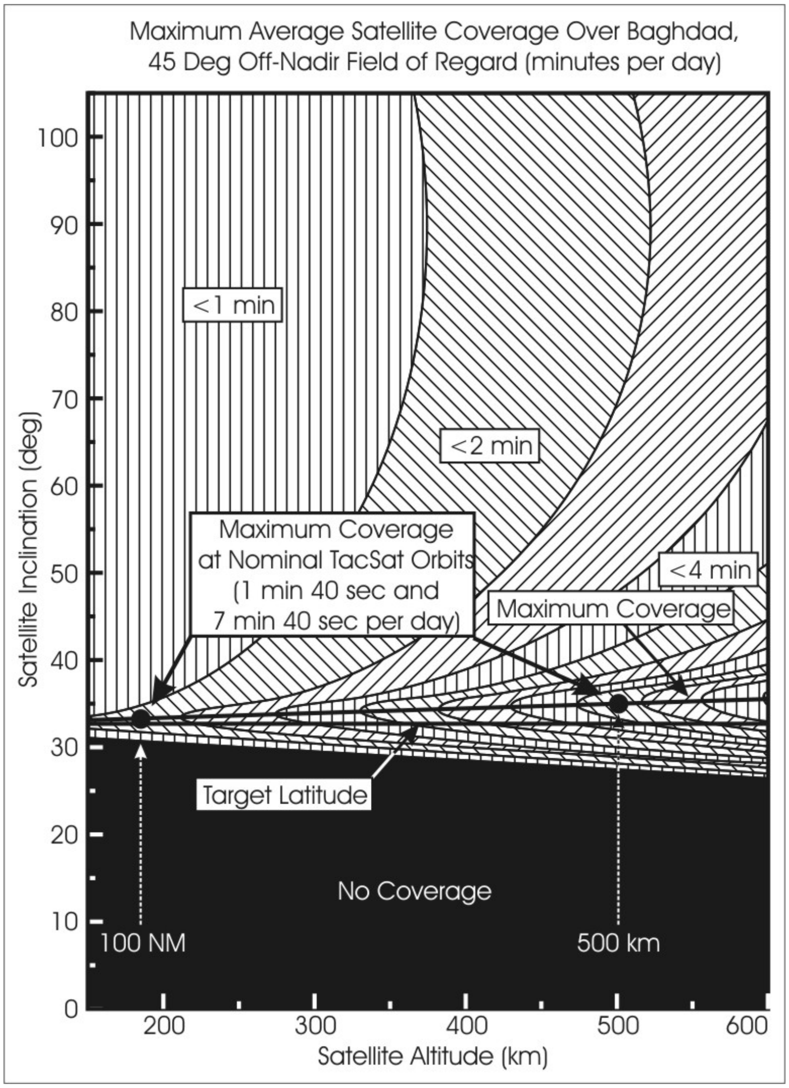


Figure 19. Long-term average contact times over Baghdad with a 45 degree off-nadir FOR.

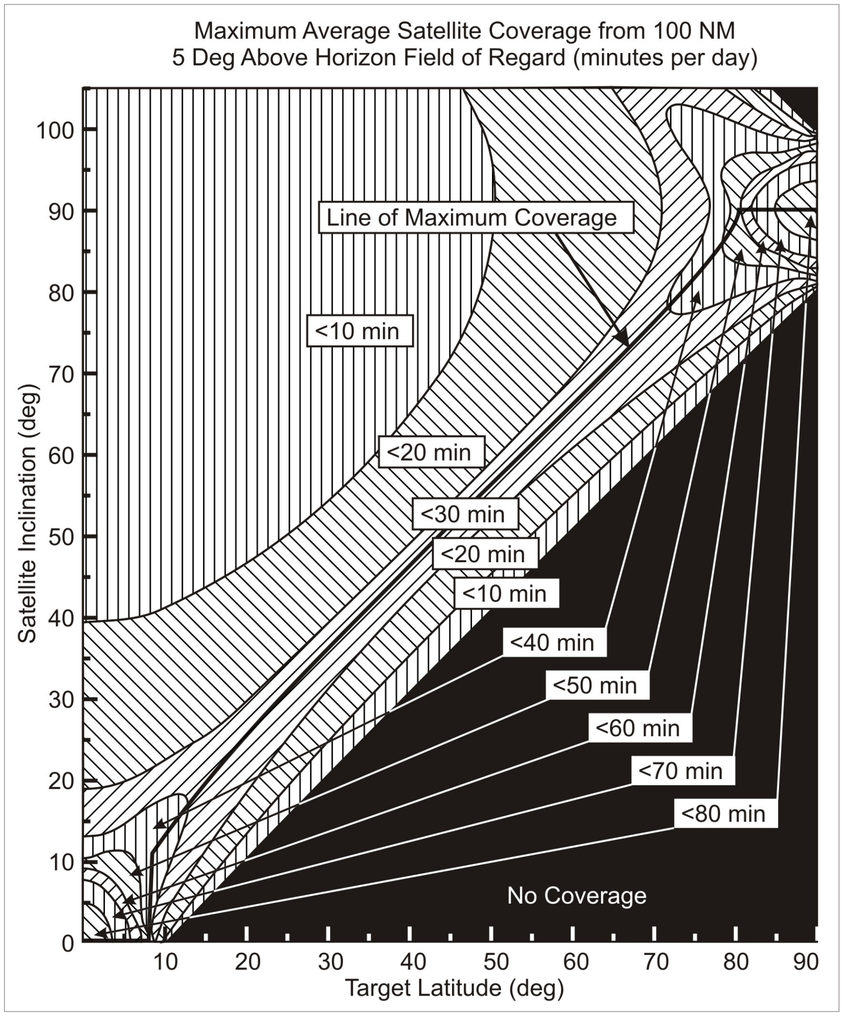


Figure 20. Five degrees above the horizon FOR satellite coverage from 100 NM (185 km).

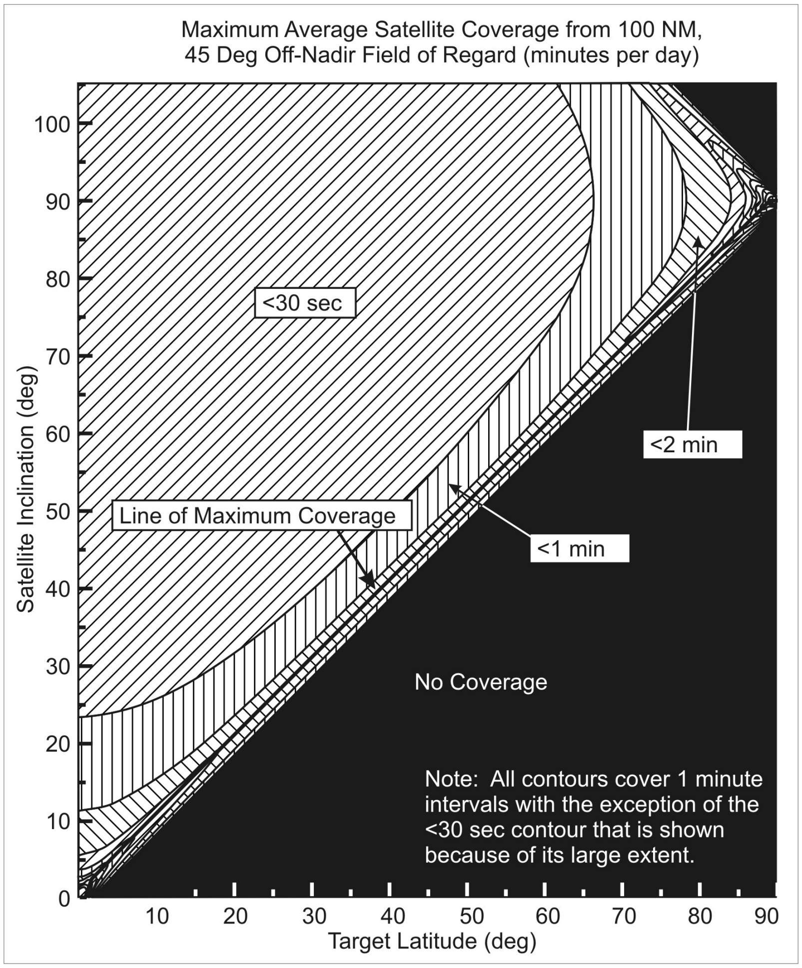


Figure 21. 45 degrees off-nadir field of regard satellite coverage from 100 NM (185 km).

Although the discussion in previous sections of this paper dealing with orbit optimization was intentionally limited to the best-case (horizon) FOR for pedagogical purposes, many of the previous figures have also included data for four other FORs: five and ten degrees above the horizon for comm/BFT missions and 30 and 45 degrees off-nadir for imagery missions. Now that we have seen why these FORs are an important, additional constraint on satellite performance, we will revisit these figures to investigate their impacts.

In keeping with the goal of giving the tactical satellite program its best chance for success when looking at operational utility, tactical satellite sensors will be assumed to have the capability to perform perfectly with the more favorable of the two FOR cases for each mission, only requiring comm/BFT satellites to be five degrees above the horizon instead of ten degrees, and allowing imagery birds to achieve full functionality all the way out to 45 degrees off-nadir instead of the commercial norm of about 30 degrees. Along with the assumptions of perfectly executed programmatics, the ability to achieve perfect technical solutions, all-weather, day/night operational capability, and the ability to place satellites into the optimal orbits for their missions, these favorable assumptions on achievable FORs will bias the results heavily in favor of tactical satellites when we later look at operational utility.

Again, this study will only consider the relatively mild FOR limitations on mission accomplishment. FOV limitations are typically much more restrictive. To illustrate this concept, the FOR for earthbound photographers with a camera would be analogous to everything they can possibly see from their location (zero to 360 degrees in azimuth and zero to 90 degrees in elevation). Their FOV would be the substantially reduced portion of the world that can be seen through their camera. As the FOV limitations are governed by the choice of the person who commands the payload and not by physics, they will not be considered here. In reality, they will severely limit what can actually be accomplished from orbit. Ignoring FOV limitations are one additional way in which this study is biased in favor of tactical satellites.

Figure 13 (p. 27) showed the optimized average daily contact times for all target latitudes and five FORs: two that are appropriate for imagery missions, two for comm/BFT missions, and one for an idealized SIGINT mission. In the figure the near-symmetry about 45 degrees latitude discussed earlier is readily apparent, as is the marked increase in coverage that polar and equatorial targets receive.[42] One point of the figure is to demonstrate the disparity between contact times over the same targets due to changes in FOR. While the horizon FOR discussed up until this point provides about 45 minutes coverage per day across most mid-latitude targets, switching to a reasonable comm/BFT FOR of five degrees above the horizon drops coverage to about 25 minutes per day for the same targets. The impact is even more severe when you consider imagery missions. Using the generous 45 degree off-nadir imagery FOR, the average coverage time drops to under two minutes per day.

While restricting the useable time overhead is the primary effect of narrowing the FOR, it also has other less noticeable effects. Figure 22 is a plot of the normalized contact times for satellites with five different FORs in 100 NM circular orbits optimized to cover Baghdad. Essentially, it is a plot of the coverage times along a vertical line at the latitude of Baghdad, 33 degrees, in Figure 9 (p. 22), Figure 20, and Figure 21. Since the maximum contact times are of such different scales between SIGINT and imagery missions, it is more useful for the present purpose to show each plot of contact time versus satellite inclination in terms of fractions of the maximum amount. From the figure, it is clear that the narrower the FOR, the more closely the optimal satellite inclination matches the target latitude, as evidenced by the steady march of the locations of the peaks toward the target latitude as the FOR is narrowed.

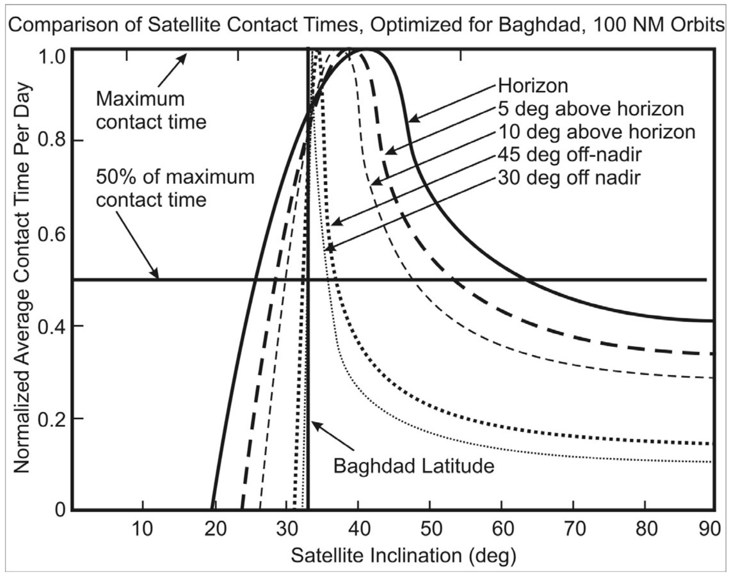


Figure 22. Comparison of the width and location of the peaks of the average daily contact times for several FORs

While the convergence of latitude and optimal inclination is a somewhat esoteric fact, a much more operationally applicable trend can also be discerned from this figure. As the FOR decreases, the width of the coverage time curve decreases markedly. Using the rather arbitrary measure of width of where the coverage time drops to half its maximum value, this trend in curve width is quite apparent. The narrowness of the average contact time curves will be discussed at more length later when we consider flexibility of retargeting in the operational utility analysis section of this paper. Table 3 summarizes the peak locations and curve widths from Figure 22 for the five FORs discussed in this study. To make this apples-to-apples FOR comparison more clear, the ground-based FORs that include reference to the horizon have been converted into satellite-based off-nadir angles in the first data row of the table. For example, for a satellite in a 100 NM orbit, the ground-based reference of five degrees above the horizon equates to a satellite-based reference of 75.5 degrees off-nadir. Those numbers represent the same physical situation, just from different points of view.

(Figures 3 and 4 (pp. 11-12) show the physical relationship between satellite-based and ground-based angles.) In the table, note the approach of the inclination of maximum contact time toward the latitude of Baghdad (33 degrees latitude) as the FOR is narrowed. Also note that the contact time becomes a very sensitive function of inclination for narrower FORs. Again, the sensitivity of this function will be discussed later in relation to the opportunistic use of tactical satellites for other than their designated targets.

Table 3. Comparison of curve parameters from Figure 22 for a satellite at 100 NM optimized for coverage of Baghdad. Inclinations and widths are given to the nearest half-degree.

General Term for FOR	Horizon (satellite-based)	5 Degrees Above Horizon (ground-based)	10 Degrees Above Horizon (ground-based)	45 Degrees Off-Nadir (satellite-based)	30 Degrees Off-Nadir (satellite-based)
Satellite-Based FOR (Degrees Off-Nadir)	76.4	75.5	73.1	45	30
Inclination of Maximum Contact Time (Degrees)	41	38.5	37	34	33.5
Width of Contact Time Curve (Degrees of Inclination)	37.5	25	18	4.5	2.5

Returning to Figure 13 (p. 27), the effect of narrowing the FOR on the amount of time per day a satellite is overhead is striking. Constraining the FOR to the comm/BFT missions essentially halves the daily amount of time overhead, while the imagery constraint shrinks the daily contact time to a few percent of its horizon value. The pass duration (Figure 12, p. 26) also shrinks markedly. The combination of these two changes has dramatic effects on the number of passes per day, average gap time, and cost per hour overhead, as demonstrated in Figure 14 (p. 28) and Figure 15 (p. 29). Tables 1 and 2 (pp. 4-5) highlight many of these differences for the Baghdad case.

Click the arrow to go to Part II ⇨